Solar Variation and the Weather.

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NEARLY a century ago three pioneers, Sir John Herschel, Pouillet, and Forbes, laid the foundations of the measurement of solar radiation. Each devised an instrument for measuring the heating effect of the solar rays and used it diligently. Pouillet and Forbes availed themselves of the law of extinction of light, which had been independently discovered about 1760 by Bouguer and Lambert, to calculate the intensity of the solar rays, as they would be outside our atmosphere. Forbes's researches in the Alps proved that this law is not strictly applicable to the sun's rays as a whole, and he was led to believe that the value of the so-called solar constant of radiation was as high as 2·85 calories per sq. cm. per min. Pouillet's value, based on the assumed validity of the Bouguer-Lambert law, was 1·76 calories.

As pointed out by Radau, the problem of estimating the intensity of the solar heat outside our atmosphere requires the study of the various spectrum rays separately, because their transmission through the atmosphere is unequal. Langley invented the spectro-bolometer about 1880, and immediately applied it to the problem as analysed by Radau. In the famous Mount Whitney expedition of 1881 Langley carried on spectro-bolometric and pyrheliometric measurements simultaneously at an altitude of 12,000 ft. Misled by certain theoretical considerations, however, these experiments seemed to him to yield the value 3·07 calories per sq. cm. per min. as the most probable value of the solar constant of radiation. A correct reduction, which he also gave in his report, yielded 2·22 calories. Later experiments made on Mount Whitney and on Teneriffe indicate that while the spectro-bolometric work was good, Langley's pyrheliometric determinations were too high, so that the true result should have been 1·9 calories.

Up to that time no fully satisfactory instrument for measuring the intensity of solar heat at the earth's surface had been perfected. About 1893 Prof. Knut Ångström's highly ingenious electrical compensation pyrheliometer fixed the scale of solar radiation measurements surely within 5 per cent. In recent years the accuracy of the Ångström pyrheliometer has reached to 2 per cent. or better. In 1913 three independent series of determinations at the Smithsonian Institution fixed the standard scale of radiation measurements now generally adopted. The Ångström scale as corrected by A. K. Ångström lies 1·8 per cent. lower.

At Washington, under Langley's direction, the spectro-bolometer, which at the time of the Mount Whitney expedition was almost unmanageable, was perfected in the decade 1890–1900 into a tractable, trustworthy instrument, and made to trace photographically an autographic solar spectrum energy curve extending from wave-length 0·3 micron to 3·0 microns within 10 minutes.

In the autumn of 1907 experiments were begun in Washington to fix a standard procedure for solar constant observations. Omitting minor details, the process which resulted is as follows: Beginning when the sun is near 15° above the horizon, about six solar spectrum energy curves, and simultaneously pyrheliometric measurements, are made, ending when the sun's altitude has reached about 60°. These curves are measured at about forty points corresponding to known wave-lengths from far in the ultra-violet to far in the infra-red. Taking each wave-length by itself, these intensities on the six separate curves follow the Bouguer-Lambert law of extinction. Hence plotting the logarithms of measured intensities as ordinates and corresponding values of the secants of the solar zenith distances as abscissæ, each group of six points determines a straight line. Producing this line to zero of abscissæ—that is, to the line corresponding to no atmosphere at all—we read there the logarithms of the intensity for the various wave-lengths, as the energy curve would be found outside our atmosphere—on the moon, for instance. The scale of energy in calories per square centimetre per minute comes by comparing the total area included under the spectro-bolometric curves with pyrheliometer readings taken simultaneously. Such, in brief, is the process.

Determinations were begun at Washington in October, 1902. In the springtime of 1903 a large drop amounting to nearly 10 per cent. was found in the values after the end of March. The changed values persisted so steadily that we were led to entertain the hypothesis that the solar radiation had actually diminished. A comparison was made between solar heat and terrestrial temperatures. It actually appeared that just after the apparent drop in solar radiation there occurred a general drop in terrestrial temperatures for all available stations of the north temperate zone. This led us to the long campaign of solar radiation observations which I shall now describe.

In 1905 we began sending yearly expeditions to observe solar radiation at Mount Wilson, California, also the seat of the famous Mount Wilson Solar Observatory of the Carnegie Institution. I am happy to acknowledge the great assistance and enthusiastic interest which Dr. Hale and his colleagues have at all times given our work there.

From the first the Mount Wilson values, though far more accurate than Washington values, owing to the clearer and more uniform sky conditions of California, showed on their face a variability over an extreme range of 10 per cent. in the emission of solar radiation. The sun appeared to be a variable star having a twofold type of variation: First, a fluctuation with the march of years attending changes in solar activity as indicated by sunspots, faculæ, prominences, etc.; secondly, a fluctuation running its courses in a few days, weeks, or months. Both types of variation are highly irregular. The longer-period type appears to reach 4 per cent. for 100 Wolf sun-spot numbers. The shorter-period changes are larger, and often amount to 3 or even 5 per cent. in a week or a fortnight. Sometimes they reach 10 per cent.

In order to test the validity of these apparent solar changes, we secured nearly simultaneous observations at Washington (sea-level) and Mount Wilson (1730 metres). Also in 1909 and 1910 at Mount Wilson and Mount Whitney (4440 metres) close agreement of results was found. Then in 1911 and 1912 we observed nearly simultaneously for several months at both Mount Wilson and Bassour, Algeria (1160 metres). Both Mount Wilson and Bassour indicated a range of solar variation of nearly 10 per cent. The coefficient of correlation between their indications in 1912, according to Mr. Knox Shaw's determination, is +58±7·9 per cent. Thus our view of the sun's short-period irregular variation was confirmed by the agreement of these results from two stations separated by one-third of the earth's circumference.

Since then we have confirmed the solar variability in many ways. Most convincing, perhaps, is the variation we have found in the distribution of radiation over the sun's disc attending changes in the solar radiation. As is well known, the sun's centre is brighter than its edges. We find that the contrast of centre to edge changes from day to day and from year to year. These twofold changes run in opposite senses with respect to increased solar radiation, and seem to indicate that the cause of the solar variation of long period is the hotter sun attending increased circulation at sun-spot maximum, while the short-interval changes are caused by changes of transparency of the sun's outer layers.

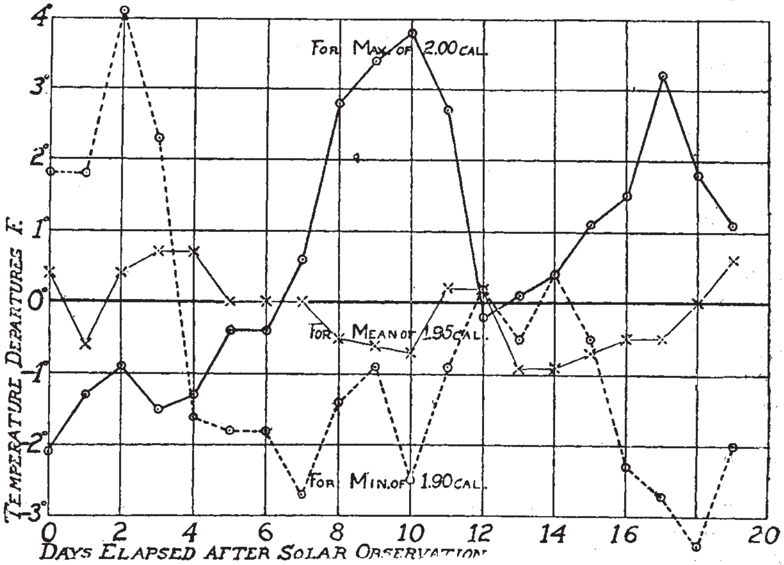

FIG 1.—The prolonged influence of solar changes on terrestrial temperatures. The three curves show the average march of temperature departures at Buenos Aires, as published by Mr. H. H. Clayton, for nineteen days next following days of maximum, mean, and minimum solar radiation in the years 1913, 1914, 1915, and 1918 for the months May to November. The solar observations were made by the Smithsonian Astrophysical Observatory at Mount Wilson, California, more than six thousand miles from Buenos Aires. The curves marked "Max.," "Mean," and "Min." correspond respectively to mean values of the "solar constant" of 2·00, 1·95, and 1·90 calories per square centimetre per minute.

In 1918 the Smithsonian Institution established a station at Calama, Chile, supposed to be one of the earth's most cloudless regions. We have been disappointed in the degree of cloudlessness, but our young men have observed the "solar constant" there on about 75 per cent. of all days since July 27, 1918. Comparisons with Mount Wilson in 1918 gave a "probable error" for one determination at a single station of 0·0111 calorie, or about 0·6 per cent. The Calama values have ranged from 1·884 to 2·028 calories, or 7 per cent.

Mr. H. H. Clayton, chief forecaster of the Argentine Meteorological Service, has compared all the Mount Wilson and Calama solar observations, 1905 to 1920 inclusive, with the temperatures and rainfall of Argentina. He finds a high degree of correlation between them. The subjoined table shows Clayton's comparison of the average marches of temperature in Buenos Aires for the years 1913, 1914, 1915, and 1918 (1916 and 1917 were not available to him), corresponding to all the occasions when the solar constant values observed at Mount Wilson fell between the stated limits. The deviations of temperature are expressed in tenths of degrees Centigrade, and range from +2·0° to −1·5° C. from the normal. The extreme and mean results are given also, translated into Fahrenheit, in Fig. 1.

Derivations from Normal Temperature in Buenos Aires following Different Intensities of Solar Radiation (May to November).

Solar radiation values in gram-calories per cm.^{2} per min.	Days following																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2·000±0·010	−12	−7	−5	−8	−7	−2	−2	3	15	16	20	14	−1	1	2	6	8	17	10	6
1·980±0·010	−1	−6	−2	−1	−8	0	6	9	9	5	5	4	7	9	5	−1	2	6	0	6
1·960±0·010	2	9	4	0	−2	−2	−2	0	−2	−2	−4	−5	−1	−4	−5	−1	−2	−3	−3	5
1·940±0·010	2	−2	1	7	9	2	2	0	−3	−4	−3	7	2	−5	−5	−6	−3	−3	3	2
1·920±0·010	9	0	−4	−4	−6	−4	−9	−5	−2	0	3	3	5	6	3	−5	−3	−7	−5	1
1·900±0·010	10	10	23	13	−9	−10	−10	−15	−8	−5	−14	−5	1	−3	2	−3	−13	−15	−19	−11

It is very striking that the solar changes produce such large and prolonged temperature effects. On the tenth and seventeenth days after the event the average temperature following solar constants of 2·00 calories differs by more than 6° F. from that following solar constants of 1·90 calories.

The temperatures following minimum "solar constant" values are generally lower than the normal from the third to the nineteenth day; they are above the normal before the third day; while those following high values are above the normal from the sixth to the nineteenth day, they are below the normal before the sixth day; and those corresponding to mean "solar constant" values differ by little from the normal through the whole interval.

The latter state of affairs is probably decidedly modified at other times of the year, for Mr. Clayton finds the following correlation coefficients connecting the temperature departures at Buenos Aires eight to nine days after the event with the solar radiation variations observed at Calama from August, 1918, to May, 1919.

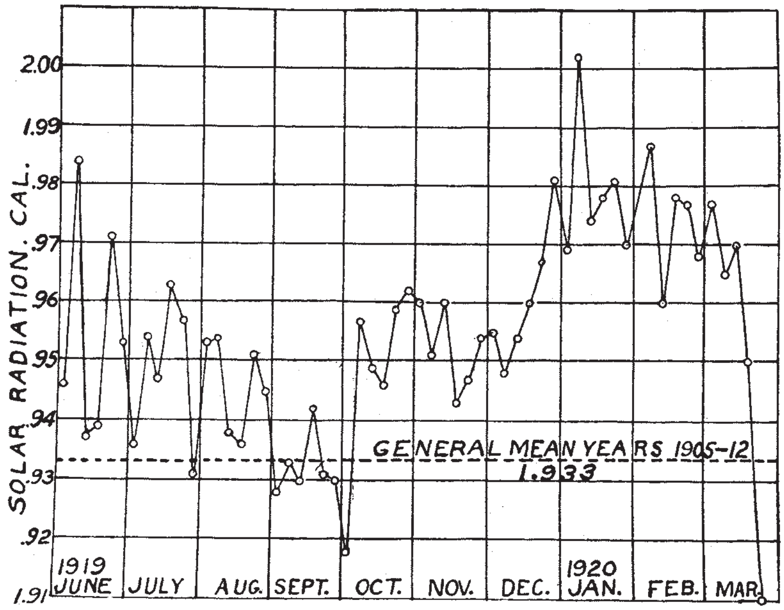

FIG. 2.—Five-day means observed at Calama, Chile, 1919-20.

Jan.	Feb.	March	April	May	June
−0·49	−0·20	+0·18	+0·23	+0·33	—
July	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
—	+0·20	+0·26	−0·23	−0·29	−0·33

Taking these figures with the figures given above, we are to conclude that while on the first three or four days after the event high solar radiation tends to produce high temperatures in Buenos Aires from October to February, the opposite tendency governs March to September.

These reversals of solar variation effects with the time of the year are paralleled by reversals with geographical position, according to Clayton, who was at first led to regard these geographical reversals as zonal. But it now seems more probable to him, I think, as well as to Nansen, that they are associated with the great atmospheric-action centres rather than with the earth's zones. As these action centres change place from time to time, it seems possible that the geographical and secular reversals merge as effects of one general cause. While it may seem extraordinary at first sight that the past winter has been exceptionally severe (at least in Eastern United States), though solar constant values have been steadily exceptionally high from early in October to February, this may be compared with the known fact that when there are many sun-spots high solar radiation and low temperatures also occur together. Unusual cloudiness or prevailing polar winds may well account for low temperatures associated with high radiation.

Clayton's studies have led him to a system of forecasting in which telegraphic reports of daily solar constant values as obtained by Smithsonian observers at Calama, Chile, take a prominent part. He claims decided and valuable success for both temperature and precipitation forecasts.

If these pioneer results should be confirmed it seems highly desirable to establish several other solar constant observatories in the most cloudless far-separated regions of the earth. By telegraphic communication all their results would be available for daily forecasts all over the world. The cost of such stations fully equipped need not exceed 25,000 dollars for the most inaccessible. The yearly cost of maintenance need not exceed 10,000 dollars. It is now merely the complete lack of funds for the purpose which withholds the Smithsonian Institution from establishing them.

Fig. 2 shows the march of "solar constant" results from June 1, 1919, to March 24, 1920. In no other period since 1903 has there been observed three consecutive months of values so high as those of the winter of 1919–20. The following rapidly falling values accompanied the extraordinary solar and terrestrial phenomena of March 22, 1920:—

Solar Radiation Values of March, 1920.

Date	Mean 11 to 17	18	19	20	21	22	23	24
Value	1·968	1·954	1·940	1·931	1·941	1·927	1·866	1·905